Formal Models for Embedded Commissioning

M. Tanyel Türkaslan-Bülbül, Ömer Akın
School of Architecture, Carnegie Mellon University

1. Why Modeling?

Building product models play a significant role for capturing the domain knowledge and supporting interoperability in the AEC industry. *Capturing the domain knowledge* is important for standardization efforts in this domain. A data model describes the attributes of the domain entities as well as how these entities are related to each other. A proper representation of this information leads to developing applications for systematic processing of domain knowledge. *Interoperability* is important for integrating model-based applications into an effortless and efficient flow through the design, construction and operation of buildings. It allows data exchange between different applications in different phases of building lifecycle.

2. Background: Building Information Models in AEC Industry

There are currently two main efforts to represent and exchange the information in the AEC industry: The ongoing development of STEP (STandard for the Exchange of Product model data) (STEP, 1999), and IFC (Industry Foundation Classes) developed by the International Alliance for Interoperability (IAI) (IAI, 2004). IAI is also developing aecXML, which represents AEC information as XML (eXtensible Markup Language) schemas (IAI, 2004). Similar to aecXML, AEX (Automating Equipment Information Exchange) is another standard developed by FIATECH utilizing the XML technology (FIATECH, 2004). Unlike the first three models, which target the entire AEC domain AEX focuses only on HVAC equipment. Besides these models, COMBINE and CIMSteel are two other, important modeling efforts in the AEC domain. COMBINE is an integrated design system of a group of building design tools that has a shared building model at the centre (COMBINE, 2004). CIMSteel is an internationally accepted standard for technical data exchange of engineering information across the entire lifecycle of steel frameworks in the digital environment (CIMSteel, 2004).

In these models we can define three approaches to building product modeling. First approach is utilized by STEP and IFC, they aim to capture whole domain information and represent it in the model. In this approach it is critical to maintain the relationships between entities and the integrity of the entire model when transmitting specific parts of the model to individual applications. In the second approach, COMBINE and CIMSteel focused on modeling the information related to a specific domain in a specific phase. Since their scope is narrower than the previous models, they cover more comprehensive information for their specific domain. The third approach is employed by aecXML and AEX. In comparison to previous models' complex and descriptive structure, they organized the information as a thin layer of common domain components, which are necessary for the efficient communication between applications.

All models follow an object-oriented approach for representing building information. They identify building components as entities with attributes. All models have an underlying modular structure in which information is encapsulated in smaller subsets. Building data is organized in levels where generic and domain specific data is separated. Generic data is sorted in resource levels and made available to other model units.

Among these models, STEP is the one whose focus is not limited to the AEC domain. STEP also covers multiple domains such as shipbuilding, mechanical design, electronics, and so on. Its approach to product modeling is inclusive, which not only models the data but also describes a language for modeling the data, identifies methods to implement the model and defines testing mechanisms for verifying if model is properly implemented. COMBINE and CIMSteel are aligned with STEP. They used STEP technology in the background but they also developed new techniques that go beyond STEP standards. The IFC effort is also closely parallels that of STEP, which is more than coincidental. It uses several resource definitions based on STEP while maintaining a focus on building data. It aims to capture all information related to a building's lifecycle and their relationships to each other. It represents the information in a hierarchical order from abstract to specific and provides a means for sharing the entire project stored in a model among diverse project participants. aecXML complements IFC's capabilities by providing support to business related interactions over the Internet. In comparison to IFC, information in aecXML is flat; there is no hierarchy between entities. Since its main concern is data exchange, the data in aecXML is structured and packaged in a transactional context. While data exchange in IFC is done over a neutral file, in aecXML it is through message exchange over the Internet. AEX's cfiXML has a similar approach for data modeling, but its focus is narrower than aecXML. AEX is concerned only about building's mechanical equipment.

During the model development process IFC, aecXML, AEX and CIMSteel follow a process oriented method. They first define the industry process from which the domain information is going to be extracted. IFC, aecXML and AEX utilize process models in this phase. COMBINE's IDM is, on the other hand, developed to integrate number of energy and HVAC design tools in a design environment. It is initially proposed as a repository and then it became a model to represent the data that is used and generated by these tools.

None of these models specifically focused on building evaluation or commissioning. But IFC, AEX, COMBINE and aecXML are modeling HVAC related data and can be used to transfer partial HVAC information.

3. Embedded Commissioning Approach

The conventional building delivery process begins with the recognition of the need for the building and concludes by the eventual decommissioning of it, after having gone through a set of predefined stages.

In the building lifecycle approach, buildings are considered to have cradle-to-grave life spans. They are modeled through a variety of different developmental phases, rather than a set, lockstep procedure. These phases include: requirement specification, design specification, facility construction, facility (de)commissioning, facility (re)occupancy, facility management, and materials recycling. They can take place, iteratively, in smaller or larger process cycles, at anytime during a building project's lifetime.

The Embedded Commissioning Model (ECM), combines the processes of commissioning and building life-cycle in order to provide a framework for managing the information exchange between them. Here, the role of commissioning is to complement each of the lifecycle phases and their interactions through timely building system evaluation.

For instance, building construction normally would begin once design specification is complete. Commissioning, at this point, would serve as the evaluation aspect of the construction process, periodically verifying the accuracy of what is being constructed against available specifications, whether these are of a design or requirement type. In response to this evaluation, the construction process would either continue as planned or be modified.

The Embedded Commissioning approach, integrating commissioning within building lifecycle phases, is intended to address the need for continuous evaluation during all phases of building lifecycle. The primary mechanism here is to execute each phase with the expectation that persistent evaluation will provide guidance for downstream decisions, based on ongoing commissioning measurements and simulations. This can potentially improve performance during all of the stages of the building lifecycle.

4. Modeling for Embedded Commissioning

In this research we developed two models for building commissioning. The first one is a process model that is developed for understanding the commissioning process. A step by step flowchart that shows how commissioning is practiced in different phases of building design and construction is developed. The second one is a product model that aims to identify and capture building commissioning data. The process model is used as a guide for developing the data model. For this purpose a normalized data set is prepared and modeled using object oriented technology and consistent with the needs of the Embedded Commissioning process.

4.1 Process Model

We define the BC process as an inclusive process flow illustrating every task, document and decision gathered from all phases of commissioning of the analysis of ASHRAE guideline. The flow chart is organized in the form of a design-bid-construct process which has five main phases: program phase, design phase, construction phase, acceptance phase and post-acceptance phase. All HVAC commissioning procedures are explained in relation to these building phases. In the flow chart, it is assumed that professionals are already selected and in every action box, who performed that task is denoted. This method makes process flow chart more readable and easy to follow.

The Process model differentiates between commissioning tasks and documents. All inputs and outputs of tasks are identified and relationships between documents are differentiated, such as part-of and transformation relations. This helps to keep track of changes in the commissioning documentation. Every document is represented as the output of a certain task. We also distinguished decision points and roles of decision makers. Accept or reject conditions are identified for decisions. In the process model every procedure is divided into simple actions. This helped us to catch and represent some key guidelines for HVAC commissioning.

Since it is important to accurately transfer design concepts, ideas and alterations from one party to another, proper documentation is an essential part of the commissioning process. In this model, it is possible to differentiate if a document is altered in a task or used only as an input. For example, in the *create design intent* task, the Owner’s Program document is used but not changed. However same task changes the Initial Design Intent document, if it is not approved by the owner (Figure 1). Design Intent is also a part of System Manual and this relationship is important to represent in the flow chart, because if Design Intent changes, the System Manual too should be updated.

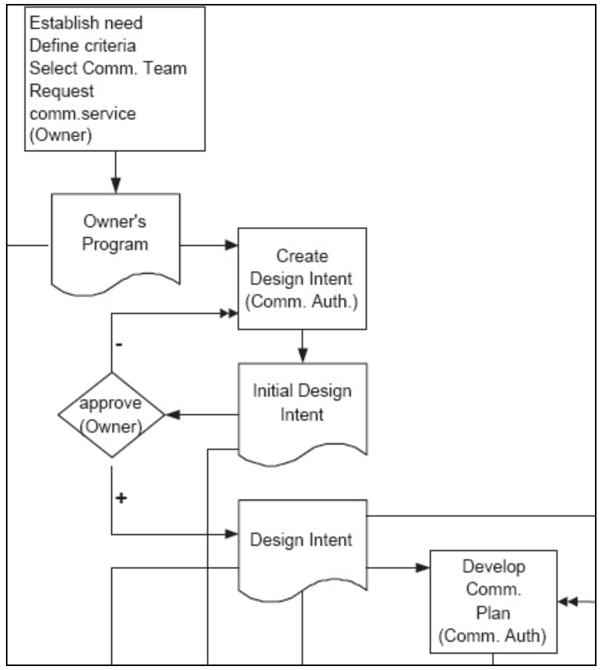

Figure 1: An example from process model

4.2 Data Model

The current data model is structured for supporting three features of the HVAC commissioning process:

The first one is the accurate and proper representation of the commissioning data. In order to model commissioning information, we first need to decide what to include in our data model. The main purpose of creating a data model is utilizing data exchange. Therefore, commissioning information that needs to be exchanged between the commissioning process and other building related activities, such as performance simulation or facility management, should be included in the data model. Not all commissioning information is needed for data exchange. Instead, they are important for reasoning purposes and capturing domain knowledge. This type of data is important for standardization in commissioning. Standardization is imperative for a systematic commissioning process.

The second feature of commissioning that needs to be represented in the data model is the differences between separate commissioning phases. The commissioning process model shows that commissioning data and evaluation procedures in every phase are not the same. For example in order to commission an Air Handling Unit (AHU) during the programming and design phases, the commissioning agent should know the system operating schedule but not the AHU make and model. In the design phase, the commissioning agent needs to evaluate the design for operability and maintainability of the AHU. Thus, enough space should be left for changing the air filter. It is not reasonable to make the same evaluation in the construction or post-construction phases. In post-construction, the commissioning agent needs to make sure that the AHU is installed properly, so the inlet/outlet ductwork installation should be inspected. This inspection cannot be done before the construction, but once the AHU is installed it should be checked periodically during the building lifecycle.

Separate phases of commissioning require different types of information. This is due to the difference in evaluation methods utilized during each phase or the unevenness in available building information. However, building commissioning data has a cumulative character. As the commissioning process proceeds towards the post-construction phase, the data becomes more detailed. In the programming phase, the AHU information is abstract and defined as a simple systems description. In the post-construction phase, the AHU commissioning information is detailed to specify all attributes of every equipment type forming that specific AHU, such as supply fan capacity, heating coil entering/leaving water temperature or clean filter pressure drop.

The third feature of commissioning that needs to be represented in the data model is relationships and associations between entities. For computationally supporting commissioning activities, topology information is important. For instance, an AHU, as a complex piece of equipment, consists of other pieces of equipment, such as coils, air filters, control sensors, supply and exhaust fans. An unlimited number of AHU configurations can be created with different combinations of these pieces of equipment. They determine the performance of the AHU. In order to evaluate the operability and maintainability of the AHU, a commissioning provider needs to check every equipment type separately and inspect their connections and sequences of operation. So relationships between equipment types forming that specific AHU should be properly represented. The current version of our data model allows entities to be defined as a combination of other entities.

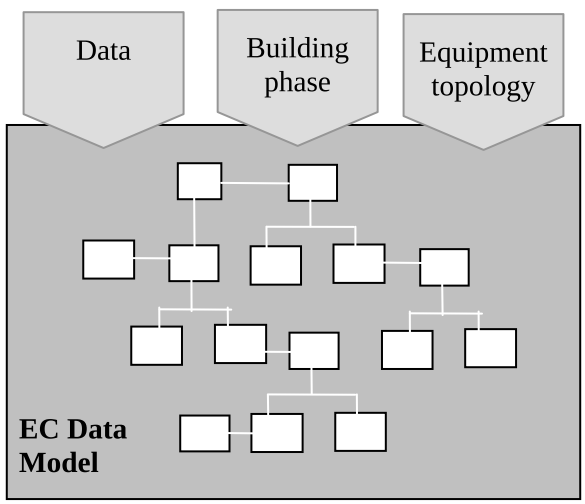

Figure 2: Three features of data model

4.2.1 Modeling Scheme

The data model is based on the assumption that there are three events in the post-construction commissioning of an HVAC equipment that define its data (Figure 3). These events are s*pecification*, *system context inspection* and *functional inspection*. *Specification* is done in the programming, design and construction phases, and it describes the performance criteria. *System context inspection* and *functional inspection* are post-construction phase events and actual commissioning takes place through these inspections. *System context inspection* is a qualitative evaluation of the equipment and its content, such as "is the inlet ductwork properly attached?" *Functional inspection* takes actual measurements and compares them with the values defined in the specification event.

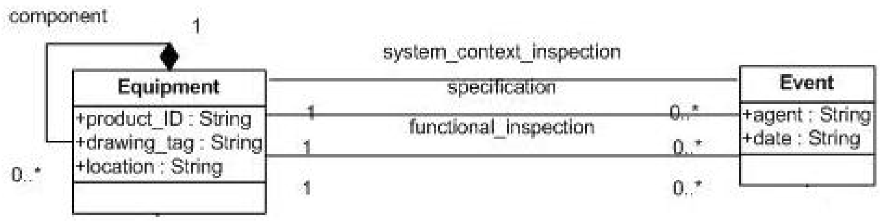

Figure 3: Three events in the post-construction phase commissioning

The data in these events are organized in a hierarchical order from more general to specific. The root of the model is the `Event` class from which `PerformanceDescription` and `Inspection` classes inherit their properties. The `PerformanceDescription` class represents the *specification* event and the `Inspection` class represents the *system context inspection* and *functional inspection* events. They are specified as `FunctionalInspection` and `SystemContextInspection` classes, in the third level. Specific information for every piece of equipment is added as branches to this structure.

Figure 4 shows an example of model branch for fans. Equipment representations in the data model show a taxonomic structure. For example vane axial fan information that is needed for *functional inspection* is modeled as a hierarchical structure. Properties that are specific to vane axial fan are kept in the `VaneAxialFanPerformance` class, which inherits some of its properties from the `FanPerformance` class. `FanPerformance` class holds general coil performance attributes and linked to the `PerformanceDescription` class. It inherits all `PerformanceDescription` and `Event` class properties. The information that is needed for the *system context inspection* of vane axial fan is modeled in a similar way. However, in this case the `FanContext` class is linked to the `SystemContextInspection` class and inherits `SystemContextInspection` and `Event` class properties. Other equipment is modeled in a way similar to the fans.

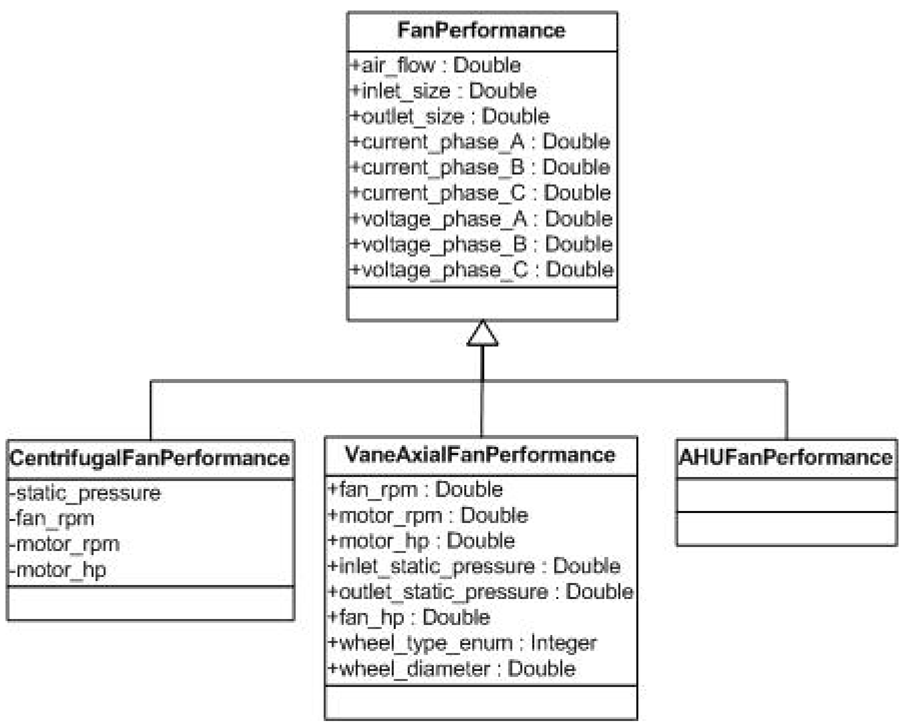

Figure 4: Fan data model for Functional Inspection

5. Testing Data Model in a Real World Commissioning Case

We will test the data model through the proposed prototype application. Tests are going to be conducted on three levels.

The first level is about testing general features of the data model, which address the problems that are related to information flow, standardization and limited computational support.

For testing the information flow, we will feed information coming from different phases of the commissioning process and trace the data backwards towards the design phase, and forwards towards the occupancy phase. This test will fail if the prototype does not allow the user trace the data. Currently it is not possible to test the data model to see if it brings a standard to the domain. But the prototype application should address this problem and allow the user to define new attribute types for equipment if they don't exist in the model. Testing the prototype to see if it provides a computational support to the commissioning process requires running the prototype in an actual commissioning environment. For this test, we will simulate the commissioning process using commissioning reports, meeting minutes and the interviews we will make with the commissioning agent.

The second level of testing is about the specific features of the prototype and the data model. These features include interoperability, efficiency of the data model structure and the usability of the data model layout.

For interoperability testing, we will exchange data between the proposed prototype and two other commissioning applications, which are developed in the Building Commissioning Research Group at CMU, through the STEP 21 file format. One of these applications is about the visualization of the commissioning data and the other one is about mapping building commissioning data to IFCs. For testing the efficiency of the data model structure, we will use the data stream collected by sensors in the HVAC system. In this test we are planning to measure the efficiency of the proposed system with an input of 24 hour continuous information.

The third level of testing is about analyzing every use case specifically. In these tests we will try minimum and maximum values with various data types. Again the real world commissioning information is going to be the guide for these tests.

7. Conclusion

The process of building commissioning generates a very large amount of data, which needs to be shared across all facility delivery phases. Supporting different phases of building evaluation from the programming phase to facility occupation requires effective commissioning tools and a flexible and powerful information model that supports these applications. However, there are potential challenges for undertaking a model based approach. Volatility is one of these challenges. Real world commissioning exists under volatile information conditions, while our data model represents only a stable group of data and any condition of unpredictability is a challenge for us. Another challenge is maintaining the model according to likely changes in our knowledge domain. The model should be capable of representing new product introductions or property updates, with ease. Because of the dynamic nature of the industry, product models should have extension functionality. Despite these challenges building product models are capable of representing more information than conventional methods used in the industry (drawings, excel sheets, checklists, etc.). Our research in ECM shows that utilizing a building information model in AEC industry can improve building evaluation activities in many phases of building lifecycle.

Acknowledgement

This project has been supported by the National Institute of Standards and Technology, Grant No. 60NANB3D1114 and No. 70NANB4D1099.

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